ANALYSIS, DESIGN AND CHARACTERIZATION OF SMALL-GAP PHOTOCONDUCTIVE DIPOLE ANTENNA FOR TERAHERTZ IMAGING APPLICATIONS

ABSTRACT

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ABSTRACT

The terahertz (THz) regime of the electromagnetic spectrum is rich because of its unique properties with the emerging possibilities in various applications such as wireless communications, imaging, non-destructive testing, security scanning and process control. The unique features of THz waves are non-ionizing radiation, better resolution than the microwave, unique spectral absorption, and an ability to propagate through dielectric materials. The spectroscopy with high spectral resolution at frequencies in THz range is an influential analytical tool for investigating the structure as well as the energy levels of molecules and atoms. Using THz spectroscopy, it is potentially possible to detect explosive and illicit drugs even though they are obscured because THz radiations can rapidly transmit through materials such as plastics, paper products, luggage, clothing and other non-conductive materials. Moreover, on comparing the measured reflectivity of the THz spectra with known calibration spectra, it is easier to identify the presence of these agents and distinguish them from benign objects.

For the imaging applications, the continuous wave (narrowband) or pulsed wave (broadband) THz systems for the generation of THz radiation is used and this classification is based on the laser source used to generate photocurrent. Moreover, the applications such as homeland security, defence as well as safety of aviation industry have placed huge demands on the growth of advanced imaging systems. However, the visible and the infrared imagery is providing high image quality, but they are mired by atmospheric obscurants such as cloud cover, dust storms, sand, smoke, fog and rain. Therefore, the THz imaging provides an attractive means to diminish or eliminate the impact of low visibility conditions due to such atmospheric conditions. Further, in close-range sensing and imaging applications, the pulsed THz sources are more favourable for acquiring depth information. The advantages of pulsed THz time-domain spectroscopy are that broad spectral information from 0.1-3 THz can be obtained using a single picoseconds THz pulse and the depth information can be achieved from the difference in arrival times of THz short pulses.

The potential challenges in the present THz pulsed imaging system includes size, cost, output power, signal-to-noise ratio (SNR), bandwidth, spatial resolution, depth penetration, water sensitivity and speed of data acquisition. Various THz applications would be benefited from the compact integration of THz devices and other types of functional devices. Moreover, for the THz imaging application there is a potential requirement of planar and compact THz

antenna sources with on-chip fabrication in addition to high directivity so as to attain large depth-of-field (DoF) for enhanced image resolution. Therefore, all the relevant literature on the current state-of-the-art pulsed THz imaging applications and potential challenges of THz antenna technology for imaging applications has been reviewed. The THz antennas which rely on photoconduction technique are the most common devices in THz systems. Among them, a photoconductive dipole antenna being simple in fabrication is the extensively utilized THz source for pulsed broadband system used in THz imaging and spectroscopy systems. A well-designed sub-wavelength (micrometer) scale photoconductive dipole antenna structure has the potential for high output power generation and broadband THz pulse emission which are useful for THz imaging system. However, the low values of gain, directivity and the low optical-to-THz conversion efficiency are the important limitations of basic photoconductive dipole antenna. Therefore, the inspiration of this research work is to theoretically ascertain the key modalities of improving photoconductive dipole antenna's performance for imaging applications. We have presented several methods/ techniques to enhance the directivity of the photoconductive dipole antenna analytically and validate the proposed models by using CST Microwave Studio simulation software.

Initially, a simple synthesis technique to find out the physical parameters of small-gap photoconductive dipole antenna is exploited. To enhance the antenna radiation efficiency which also contributes to the total efficiency of photoconductive dipole antenna, a thin superstrate below the dipole antenna is employed which also enables the antenna to withstand high biased voltage. Moreover, to have a diffraction limited imaging, there is a requirement to design an antenna of shorter wavelength. Consequently, the proposed antenna design is compact in size. Further the use of silicon lens with the designed antenna configuration helps in focusing the beam in the desired direction. In addition, the proposed photoconductive dipole antenna with silicon lens improves the antenna performance which is potentially helpful for THz sensing and imaging applications such as the detection of hidden explosives and some commonly used explosive related compounds whose spectral absorption peaks lies in 1-2THz range. By using proposed simple photoconductive dipole antenna along with thin superstrate and silicon lens, we have attained the directivity 10.7dBi and radiation efficiency of 91.59% in both E-plane and H-plane.

Further, there are certain modalities for improving the photoconductive dipole antenna performance which must be identified to achieve high THz average radiated power with improved total efficiency. Therefore, a thorough systematic framework to assess the physical

phenomenon occurring across the small-gap photoconductive dipole antenna is determined using an analytical procedure utilizing explicit mathematical expression. A pragmatic description of the small-gap photoconductive dipole antenna which gives a relationship between the parameters of equivalent circuit model and dimensions of antenna electrodes is presented. The effects of biased lines on the photoconductive dipole antenna performance parameters are examined with the help of proposed equivalent circuit model. Moreover, the performance of antenna is also examined with variation in the photoconductive gap size for the time-dependent physical phenomenons like time-dependent source capacitance, source conductance, and radiated voltage across the antenna electrodes and THz radiated power and the total antenna efficiency of the photoconductive dipole antenna. The insight of distributed components for half-wavelength planar biased-lines helps to get better impedance matching efficiency of the antenna which results into an increase in the total antenna efficiency. The optimization of size of photoconductive gap to improve the total antenna efficiency is examined and its effect on radiated power is determined.

To enhance the directivity of small-gap photoconductive dipole antenna, the frequency selective surface (FSS) as bandpass spatial filter is employed with the antenna. Further, to preserve the purity of incoming THz wave on the receiving antenna side where the electromagnetic interference (EMI) is the major hindrance, the use of FSS structure with antenna geometry in THz region is beneficial to enhance the antenna performance parameters. The physical parameters of proposed bandpass FSS with photoconductive dipole antenna are obtained using simple synthesis technique of a single square loop bandpass FSS. Further, the effect of unit-cell periodicity and slot-size of FSS on the resonance condition, gain, directivity as well as the front-to-back lobe ratio of photoconductive dipole antenna structure is investigated.

In addition to this, the photoconductive dipole antenna array is also formed on a single photoconductive substrate to make it compact and suitable for THz imaging applications. The photoconductive dipole array antenna improves the gain and directivity and therefore, is useful to enhance the imaging capabilities to address the considerations such as limited depth-of-field (DoF) i.e. the distance over which an object is judged in focus and size-weight-and-power (SWaP) of THz source for imaging applications. These are important considerations for applications like stand-off imaging and surveillance of moving targets where the high angular resolution as well as extended depth-of-field is the key parameters for successful detection of hidden explosives and illicit drugs. The designed antenna array

configuration provides a radiation efficiency upto 72% for (1×2) and 84% for (2×2) PCA array, respectively. A directivity enhancement technique of using FSS with photoconductive dipole antenna array is also proposed without using a lens-system to limit the fabrication complexity in array configuration of the THz radiating structure to yield high image resolution. Using the FSS superstrate with array configuration, the directivity is increased by 4.55dBi in E-plane and 4.66dBi in H-plane for (1×2) array assembly and 6.95dBi in E-plane and 6.96dBi in H-plane for (2×2) array assembly at the resonance frequency 1.95THz. The proposed antenna array with FSS results into planar configuration of highly directive radiating THz source for the imaging applications. Moreover, by using this technique, radiation energy become confined to the desired frequency band rather than spreading over a wide spectrum range. The complete antenna array assembly with FSS is made useful to outline an image by scanning a single beam in both the principle planes. Further, the functioning of beam-steering phenomenon in planar array of photoconductive dipole antenna using progressive phase-shift for sensing and imaging application is a challenging issue. A highly directive (2×2) small-gap photoconductive dipole phased array antenna has been realized and the beam steering characteristics of the small antenna array configuration at 1.95 THz operating frequency is presented. With progressive phase shift of 10° for the scanning range $0° \leq \theta \leq 40°$ with $\varphi = 0°$ along x-axis as well as y-axis antenna elements of the array, the simulation results show the occurrence of beam steering by 3° in E-Plane and 1° in H-Plane, respectively

However, for the proposed small-gap photoconductive dipole antenna, there are certain design techniques which can be integrated such as using the dielectric structure with periodic LT-GaAs strips inside the gap area and use of anti-reflection coating materials on the surface of photoconductive substrate for future work. These techniques will help to improve the laser-to-electrical conversion efficiency of the antenna which contributes into the total efficiency of the antenna. A graphene based artificial magnetic conductor for directivity enhancement of photoconductive dipole antenna can be investigated for tunable antenna applications in THz pulsed imaging system.